Zodiacal Infrared Foreground Prediction for Space Based Infrared Interferometer Missions

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Abstract. The zodiacal foreground for a highly sensitive space infrared interferometer is predicted for various observing locations. For the predictions we use a model that was derived from measurements of the Cosmic Background Explorer (COBE). We find that at a wavelength of 10 μm 96% of the sky is darker than 1 $MJy\,\mathrm{sr}^{-1}$ for observations in the ecliptic plane at 5 AU, and 83% is darker than 0.1 MJy sr^{-1}. At 1 AU, however, always more than 50% of the sky are brighter than 1 MJy sr^{-1}, even if the observations are made from 30° or 60° of latitude above the ecliptic plane, at 10 or 20 μm. Thus, according to the employed model, the foreground reduction by increasing the heliocentric distance of the observing location is more effective than by increasing the latitude.

Keywords: Interplanetary dust, zodiacal light, infrared radiation, mission analysis

1. Introduction

The search for extra-solar planets (exo-planets hereafter for brevity) and possibly for primitive forms of life on them has received much attention since the mid-1990s and is pursued by NASA and ESA. In its studies ESA follows a proposal by Léger (1996) of a space infrared interferometer, for which initially five 1 m-class telescopes were envisioned. More recent designs of the interferometer, which was named DARWIN, use six 1.5 m telescopes. At NASA a similar instrument with the name of Terrestrial Planet Finder (TPF) is under development. In addition to the search for exo-planets such an interferometer could also be used for general purpose astronomical imaging and spectroscopy. While this paper is intended to support the mission analysis for DARWIN and TPF, it is independent from the actual baseline mission scenarios.

One of the main problems for the detection and analysis of Earth-sized exo-planets is the considerable amount of zodiacal infrared foreground radiation emitted by the interplanetary dust cloud. In the vicinity of the Earth either large telescopes have to be used (Angel, 1989) or the observations have to be integrated over long periods of time in order

to sufficiently suppress the zodiacal foreground contribution (ESA-SCI, 200x). The alternative proposal by Léger is to place the interferometer at a larger heliocentric distance, where the zodiacal foreground in the 10-to-20 μm range is reduced due to the lower interplanetary dust density and lower dust temperatures. There the zodiacal foreground becomes comparable to other sources of noise, like the radiation leakage from the central star. As an alternative to larger heliocentric distances it is conceivable that the zodiacal infrared radiation is reduced at higher ecliptic latitudes. In order to cover the proposed orbit options, we investigate heliocentric orbits with aphelia at 1, 3, and 5 AU and inclinations of 30° and 60° (Jehn and Hechler, 1997).

In this paper we determine the zodiacal infrared emission at various locations (heliocentric distances and ecliptic latitudes) in the solar system using a model by Kelsall et al. (1998). This model was fit to the data taken by the COBE infrared satellite. We will discuss our choice of the dust model below.

The result of our analysis is the fraction of the sky where the zodiacal foreground is of the same order as the other noise contributors, which is $\dot{N}_{ZL} \approx 2 \times 10^4\,\mathrm{photons\,hour}^{-1}$. At $10\,\mu$m this translates to a maximum foreground surface brightness of $\approx 0.1\,\mathrm{MJy\,sr}^{-1}$ for 1.5 m telescopes, an interferometric transmission of 20 %, a spectral resolution of 20, and a field of view opening angle of 3.4 arcsec.

2. Zodiacal Dust Model

Up to date, no infrared telescope has been flown beyond 1 AU or out of the ecliptic plane. We therefore have to rely on models to determine the zodiacal infrared foreground at the suggested locations of the interferometer. If we assume that the dust emits blackbody radiation, the dust model has to provide the spatial distribution of the cross section and the temperature of the dust grains in order to determine the infrared brightness.

There exist a number of interplanetary dust models that are derived from zodiacal light and infrared observations, as well as in situ measurements. Our approach here is to use the phenomenological model by Kelsall et al. (1998), that was derived from the measurements of the COBE/DIRBE instrument. The COBE/DIRBE measurements represent the most accurate sky survey at infrared wavelengths between 1.25 μm and 240 μm so far. The Kelsall et al. model describes the interplanetary dust cloud as made up of three components: a smooth lenticular cloud, dust bands generated by collisions within asteroid families (Dermott et al., 1994), and the Earth-resonant dust ring (Reach

et al., 1995). We only consider the dominant contribution from the smooth cloud.

The drawback of our approach is that, since COBE was an Earth orbiting satellite, the model is only well constrained for predictions at 1 AU in the ecliptic. Thus the prediction of an observation at, for example, $z = 1$ AU above the ecliptic plane along a line of sight towards the ecliptic north pole is uncertain, because it is not known how much of the brightness measured by COBE at $z = 0$ along the same line of sight is generated at $0\,\mathrm{AU} \leq z \leq 1\,\mathrm{AU}$, and how much at $z > 1$ AU. However, the COBE observations along lines of sight with different ecliptic latitudes do constrain the vertical profile given by the model, whereas the radial profile is constrained by lines of sight with different ecliptic longitudes. The use of the Kelsall et al. model has the advantage that we don't have to make assumptions about the grain size distribution, because it is based on infrared observations which depend only on the spatial cross section density, not the spatial particle number density. The model also does not consider different grain temperatures for different grain sizes, it applies an *average* grain temperature that depends only on the distance from the Sun.

We summarize the Kelsall et al. model. The Infrared brightness I_λ along a line of sight (LOS) is given by

$$\begin{aligned} I_\lambda &= \int_{\mathrm{LOS}} ds\, n_{\mathrm{cs}}(\vec{r}(s)) B_\lambda(T) \qquad (1) \\ B_\lambda(T) &= \frac{2hc^2}{\lambda^5} \frac{1}{\exp \frac{hc}{\lambda k T} - 1} \\ T(\vec{r}) &= T_0 \, |\vec{r}|^{-\delta}, \end{aligned}$$

where h is the Planck constant, c the speed of light, and k the Boltzmann constant. The parameters $T_0 = 286K$ and $\delta = 0.467$ were fitted to the COBE data. Considering the offset and the tilt of the zodiacal cloud with respect to the ecliptic plane, the cross section density n_{cs} is

$$\begin{aligned} n_{\mathrm{cs}}(\vec{r}) &= n_0 \left(\frac{r'}{r_0}\right)^{-\alpha} f(\zeta) \qquad (2) \\ r' &= \sqrt{x'^2 + y'^2 + z'^2} \\ x' &= x - x_0 \\ y' &= y - y_0 \\ z' &= z - z_0 \\ f(\zeta) &= \exp(-\beta g^\gamma) \end{aligned}$$

$$g = \begin{cases} \frac{\zeta^2}{2\mu} & \text{for } \zeta < \mu \\ \zeta - \frac{\mu}{2} & \text{for } \zeta \geq \mu \end{cases} \tag{3}$$
$$\zeta = \left| \frac{z''}{r'} \right|$$
$$z'' = x' \sin\Omega \sin i - y' \cos\Omega \sin i + z' \cos i$$

The parameters are: $r_0 = 1$ AU, $n_0 = 1.13 \times 10^{-7}$ AU^{-1}, $\alpha = 1.34$, $\beta = 4.14$, $\gamma = 0.942$, $\mu = 0.189$, $i = 2.03°$, $\Omega = 77.7°$, $x_0 = 0.0119$ AU, $y_0 = 0.00548$ AU, and $z_0 = -0.00215$ AU.

Note that we have not applied a color correction and assume an albedo of 0 and an infrared emissivity of 1. Figure 2 shows the infrared radiation emitted by the smooth interplanetary dust cloud, predicted by the Kelsall et al. model. At the shorter wavelengths the radiation

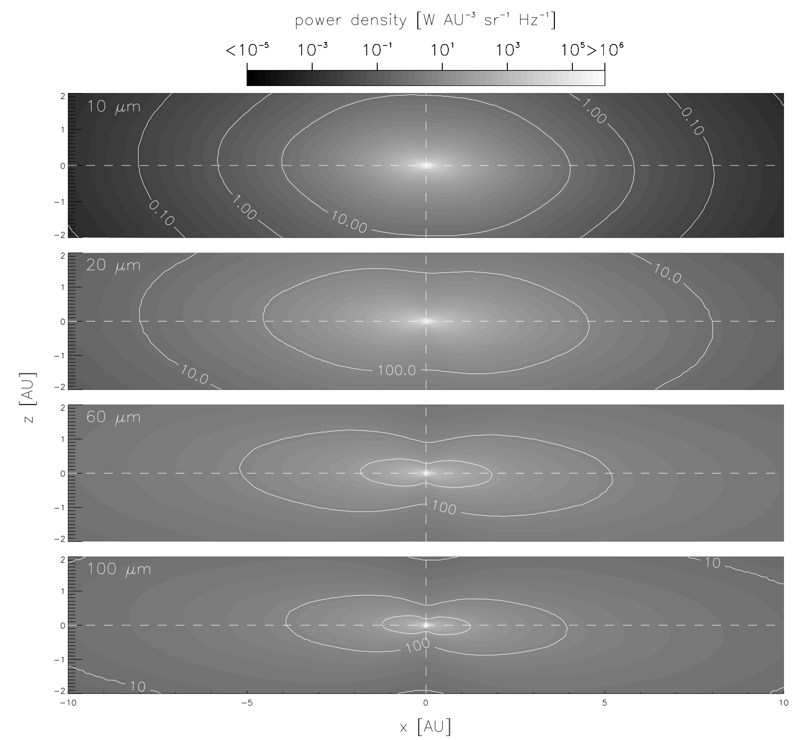

Figure 1. Power distribution radiated by the interplanetary dust cloud according to the Kelsall et al. (1998) model at 10, 20, 60, and 100 μm. The z-direction is perpendicular to the ecliptic plane and the x-axis points towards the vernal equinox.

is emitted from the region closer to the sun, whereas the more distant regions contribute more to the radiation at longer wavelengths. Thus, at 10 μm the zodiacal foreground is more localized.

3. Sky Visibility Prediction as Function of the Selected Orbit

We predict the infrared brightness received from the zodiacal foreground along lines of sight distributed over the whole sky. To represent the direction of the line of sight we use two angles : the solar-relative ecliptic longitude $\lambda_{\mathrm{ECL}} - \lambda_{\mathrm{ECL},\odot}$ and the ecliptic latitude β_{ECL}. Figure 3 shows sky maps of the zodiacal foreground brightness I_ν for in-ecliptic orbits at heliocentric distances of 1, 3, and 5 AU. Due to the localized

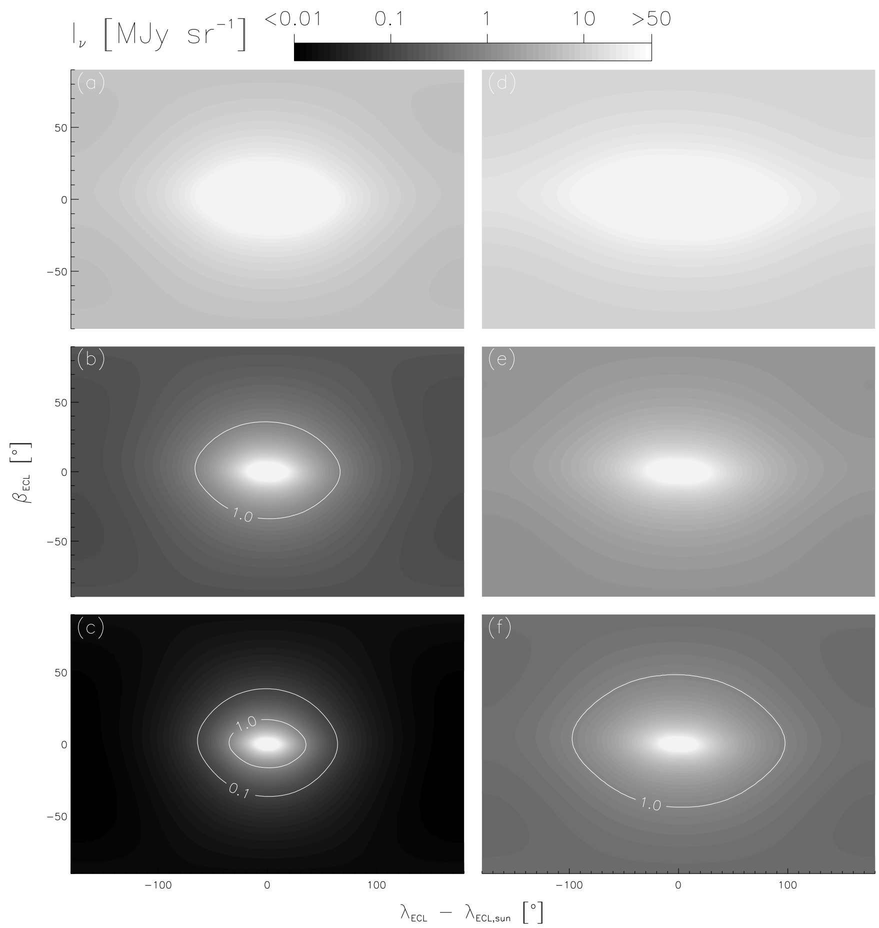

Figure 2. Sky maps of the infrared surface brightness I_ν of the zodiacal foreground at 10 μm (a), (b), (c), and 20 μm (d), (e), (f). Panels (a) and (d) show the brightness at an in-ecliptic observing location at 1 AU, in (b) and (e) the observation is made at a heliocentric distance of 3 AU, and panels (c) and (f) show the brightness at 5 AU. The contour lines show limiting foreground brightnesses of 0.1 and 1 MJy sr^{-1}.

nature of the 10 μm radiation, the installation of the interferometer at larger heliocentric distances is very effective in the reduction of the

foreground brightness at 10 μm. The reduction is at least two orders of magnitude in most regions of the sky. The 20 μm brightness is less affected, but still significantly reduced at larger distances.

We show sky maps of the foreground at observing locations 1 AU from the Sun, at ecliptic latitudes of 30° and 60° in figure 3. According

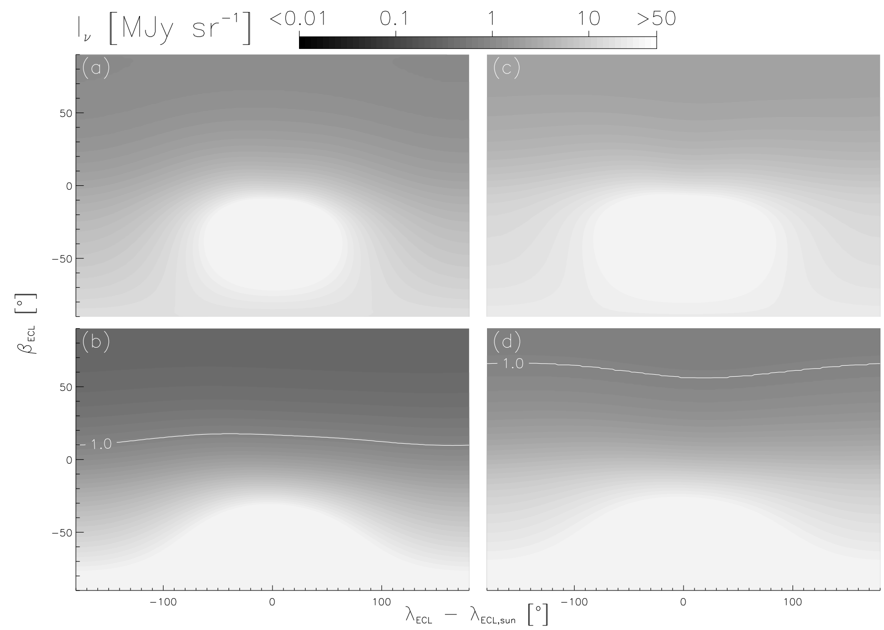

Figure 3. Sky maps of the infrared surface brightness I_ν of the zodiacal foreground at 10 μm (a), (b), and 20 μm (c), (d). Panels (a) and (c) show the brightness at an observing location at 30° ecliptic latitude and 1 AU, and panels (b) and (d) show the brightness at 60° ecliptic latitude. The contour lines show limiting foreground brightnesses of 0.1 and 1 MJy sr^{-1}.

to the Kelsall et al. model, the zodiacal infrared foreground for lines of sight towards the ecliptic north pole is reduced by one to two orders of magnitude, if an observing location 60° above the ecliptic plane is selected. The reduction factor is about the same at 10 and 20 μm. Table 3 shows the fraction of solid angle of the sky that is darker than 0.1 or 1 MJy sr^{-1} at 10 and 20 μm.

4. Discussion

We have predicted the zodiacal foreground brightness at observing locations in the ecliptic at 1, 3, and 5 AU, as well as at 30° and 60° above the ecliptic at 1 AU using the Kelsall et al. (1998) model. Since the model is constrained only by observations at 1 AU in the ecliptic plane, the predictions have to be taken with caution, especially at high latitudes.

Table I. Fraction of the sky with a zodiacal foreground brightness below 0.1 and 1 MJy sr^{-1}.

heliocentric distance[1]	ecliptic latitude[1]	fraction of dark sky (< 0.1 MJy sr^{-1}) 10 μm	20 μm	fraction of dark sky (< 1 MJy sr^{-1}) 10 μm	20 μm
1 AU	0°	0%	0%	0%	0%
1 AU	30°	0%	0%	0%	0%
1 AU	60°	0%	0%	38%	6%
3 AU	0°	0%	0%	83%	0%
5 AU	0°	83%	0%	96%	70%

[1] of observer's location

The validity of the model within the ecliptic plane at larger heliocentric distances is supported by zodiacal light observations by imaging photo-polarimeter on board the Pioneer 10 spacecraft (Hanner et al., 1976). From the Pioneer measurements it was concluded that the dust density decreases as $r^{-\nu}$ with heliocentric distance r, and the best-fit value for ν is 1.0 to 1.5. This is in accord with the radial exponent of -1.34 used in the Kelsall et al. model.

As an alternative to the Kelsall et al. model we could have used a model derived from in situ measurements, like the Divine (1993) model. The Divine model was fit to, amongst others, in situ data that was collected at high ecliptic latitudes by the Ulysses spacecraft. It has to be considered, however, that the in situ measurements are dominated by particles that are much smaller (0.1 to 1 μm) than those that dominantly contribute to the zodiacal infrared emission (10 to 100 μm). Additional constraints to the high latitude population of interplanetary dust in the Divine model come from radar meteor measurements, which allow the determination of meteoroid orbits. Radar meteors give valuable information about the inclination distribution of interplanetary meteoroids. However, all observed radar meteors are caused by Earth-crossing meteoroids, which introduces a bias to the dataset.

In summary it seems worthwhile to do the same prediction, that we have made with the Kelsall et al. model, with the Divine model for comparison. This would improve our confidence in the projected zodiacal brightness at the high-latitude observing position. We found, however, that the Divine model predicts an infrared brightness at 1 AU in the ecliptic that are about a factor of 4 too low compared with the COBE measurements along the same line of sight. Since the Divine model was also fit to observations by the Infrared Astronomical Satellite

(IRAS) (Staubach et al., 1993), and the brightness measured by IRAS is in agreement with the COBE measurements, we conclude that an error in the fit procedure lead to wrong grain temperatures. Staubach et al. (1993) report temperatures of 187 K for macroscopic (100 μm) grains at 1 AU, which is in deed very low. Only extremely reflective material would reach such a low equilibrium temperature at 1 AU. Kelsall et al. (1998) use an average grain temperature at 1 AU of 286 K. Whatever the solution to the problem is, the discrepancy of the values shown by Staubach et al. (1993) in their figures 3 and 4, and the numbers calculated with their equations (1) - (3) has to be resolved before the Divine model can be used to predict the infrared brightness.

5. Conclusion

Our calculations have shown that an orbit with an aphelion at around 5AU offers a better sky coverage (i.e.percentage of the sky for which the zodiacal foreground is below a certain level) than an inclined orbit at 1 AU. Even on orbits with inclinations of 60°, the infrared emission of the zodiacal light prohibits the detection of exo-planets in large parts of the sky. In order to reach such orbital inclinations enormous changes in the orbital velocity are required that are not feasible with conventional chemical propulsion systems and that are very costly with electric propulsion engines (Jehn and Hechler, 1997). Therefore, for infrared interferometer missions that are affected by the zodiacal infrared foreground, like the proposed DARWIN mission, orbits in the ecliptic plane with an aphelion around 5 AU are more promising.

The strong model dependence of our prediction for observing locations outside 1 AU shows, that precursor missions dedicated to make infrared measurements between 1 and 5 AU are desirable.

Finally it has to be mentioned that during this investigation the baseline for the DARWIN mission has changed. Now the interferometer is planned to be installed in one of the quasi-stable Sun-Earth libration points (probably L_2), which lie 1.5×10^6 km from the Earth on the Sun-Earth line, in order to increase the reliability and to simplify operations and communications (ESA-SCI, 200x). At this observing location the photon noise from the zodiacal foreground dominates all other sources of noise like leaking starlight, detector noise, and galactic background. As can be seen in figures 3 (a) and (d) we expect the zodiacal foreground to be in the order of 10 MJy sr^{-1} at 10 μm. This means that in order to reduce the signal to noise ratio to a level where a terrestrial exo-planets can be detected, the observation of the target star has to be integrated over a long period of time.

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